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Assessing future meteorological stresses for grain maize in France

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ABSTRACT

Recent climate change has already affected maize cropping in France allowing for example earlier sowing dates in southern France and the growth of early season varieties in northern parts of the country. The climate will continue to evolve as discussed in all IPCC reports and there is a need for farmers, seed companies and agricultural cooperative corporations to be able to anticipate those changes. The ambition of our work is to provide them with the means to get ready to adapt by analyzing a) the time evolution of meteorological stresses and certain management practices throughout the crop's growth cycle, b) the impacts of climate-induced changes in calculated sowing dates on those stresses and practices. We have applied the method we developed in a former paper to study the climatic suitability of maize in two contrasted areas of France, Ile-de-France in the North and Midi-Pyrénées in the South. Three climate change scenarios, two climate models and two maize varieties distinct in terms of precocity were used to try and ensure meaningful results. Whatever the scenario, model and variety, maize will be sown earlier than it is currently the case in both regions, especially in Midi-Pyrénées. Whatever the sowing date, rising temperatures in the future will be favorable for late varieties in the current cooler areas, and therefore even farmers in Ile-de-France will be able to grow varieties with a wide range of crop cycle length. However heat and water stress will increase in both regions between flowering and maturity, irrespective of the sowing date and scenario, thereby limiting the possibility to achieve potential yields. In Midi-Pyrénées compromises will need to be found between early sowing to minimize some later stress and increasing risks of frost during emergence, that do not currently exist.

1. Introduction

France is the leading producer of grain maize and the third largest producer of silage maize in Europe (Eurostat, 2014). Grain maize (*Zea mays* L.) is the number one feed crop in this country, the second in terms of cultivated area after wheat, and it covers about 6% of the national agricultural area (Agreste, 2014; Eurostat, 2014). Two main production areas are distinguishable in France with very diverse climate envelops, namely the north-east area representing 18% of the national surface area and 15% of the national production; and the south-west area (Aquitaine, Poitou-Charentes, Midi-Pyrénées), representing 60% of the national surface area and contributing to 60% of the production.

In the future, maize will probably remain an important crop in the French agricultural landscape because of a demand for this crop in the developing world that is expected to double by 2050 (Rosegrant et al., 2009). However, climatic conditions are changing in ranges that are likely to alter maize cropping (Bassu et al., 2014). The expected impacts in Europe from the questionnaires of Olesen et al. (2011) are shorter growth duration in most of the continental, western and Mediterranean areas of Europe, more suitable days for harvest and a decrease of late frost risk along with an increase of heat and water stress risks Europe-wide. In their simulation study of the impacts of climate change on many species in France, Brisson and Levrault (2010) predicted an advancement of the timing of maize flowering leading to the grain filling process during dryer and hotter periods. Finally, several simulation studies in Europe and France predict a negative influence of climate change (mainly temperature increase) on modeled yield despite the positive effect of the increase in CO_2 concentration (Brisson and Levrault, 2010; Bassu et al., 2014; Angulo et al., 2013).

Understanding the periods and the type of meteorological stresses that will affect maize in the future should be of great interest to many stakeholders in agriculture. Indeed, planners, land managers, and plant breeders could use this information to recommend and tailor strategies to improve agriculture performances. A general assessment of future meteorological stresses on maize cropping means considering impacts on phenology (successfully completing the crop cycle), vegetative and reproductive growth, grain quality (sugar or protein content) and the performance of cultural practices.

In a previous study, we developed a generic method to assess the climate suitability for different crop types, based on the sub-annual

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analysis of agroclimatic indicators (Holzkämper et al., 2013) calculated during main phenological periods. We have proposed to call them ecoclimatic indicators (Caubel et al., 2015). The application of the method in past and current climatic conditions proved to be effective in providing quantitative information on the stresses acting on particular plant processes (e.g. heat stress during grain filling) or on the number of days available to carry out cultural practices (e.g. days available for harvest according to risk of waterlogged soil compaction by machinery). The limited amount of required input data further promotes its use in climate change scenarios and on various spatial scales (farm, region, and country) in order to explore future possibilities for agriculture in many areas. This method can be considered as complementary to process-based crop growth models, which take into account the interactions between physiological processes and consider other environmental (e.g. soil properties) or economic factors (Holzkämper et al., 2015).

In this work, we apply this method to assess when and what meteorological stresses will affect future grain maize crops in France, regarding phenology, growth cycle, grain quality and days available to carry out the main cultural practices. We have considered three climate change scenarios, two global climate models, and one method to downscale climate change at the resolution of France to take into account the main sources of uncertainty in climate change studies. The study was performed for two maize varieties that are notable in terms of precocity, and two maize productive regions as study areas: the Ile-de-France and Midi-Pyrénées regions (Fig. 1). The evaluation was performed with a calculated sowing date designed to mimic an adaptation of farmers' behavior to climate change. Consequences on phenology and meteorological stresses helping to decide where and when to sow to improve maize potential suitability will therefore be analyzed and discussed.

2. Materials and methods

This study was conducted in two climatically contrasted regions, Ile-de-France in the northern part of the country (Lat. 48.2°N to 49.3°N, Lon. 1.2° to 3.8°E) and Midi-Pyrénées in the south-west France (Lat. 43.14°N to 44.96°N, Lon. -0.09°E to 3.14°E; Fig. 1). Ile-de-France is characterized by a quite homogeneous degraded oceanic climate, according to the classification and nomenclature developed by Joly et al. (2010); Joly's class hereafter: mean annual temperature of ~11 °C, with ~8–14 days/year with temperature below −5 °C; annual cumulated rainfall is below 700 mm, quite evenly distributed throughout the year although slightly lower during summer time. Midi-Pyrénées experiences a relatively large gradient of Joly's climate classes: altered Oceanic, semi-continental and alpine climates coexist in the region. Climate is on average considerably warmer (≥13 °C) than in Ile-de-France, and there are many days with a temperature exceeding 25 °C while almost none with temperature below −5 °C; the amount of rainfall is about the same as in Ile-de-France but with a marked seasonal cycle (summer dry season) and a smaller number of rainy days. Insolation is quite larger than in Ile-de-France. Midi-Pyrénées is already a major irrigated maize producer, while Ile-de-France has only recently become an area for irrigated short season maize, due to recent climate warming together with technical and breeding progress.

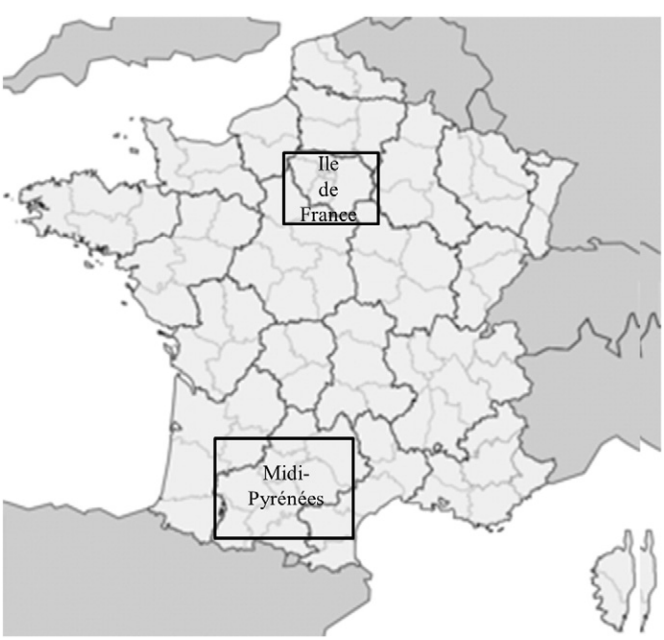

Fig. 1. The two studied areas of France.

2.1. Input data

Historical series of daily climatic data (rainfall, maximal temperature, minimal temperature, mean temperature, solar radiation, and wind speed) in both areas were retrieved from the SAFRAN historical reanalysis, which covers France at 8 × 8 km resolution for the 1950–2011 period (Vidal et al., 2009). Future changes in the 2012–2100 period have been obtained at the same spatial resolution using downscaled and bias-corrected climate changes from the fourth Intergovernmental Panel on Climate Change (Change, 2007) climate simulations. The downscaling and bias-corrected method was developed by Pagé et al. (2009) and applied to the global climate models CNCM and ARPEGE (Gibelin and Deque, 2003). We considered three IPCC SRES (Special Report on Emissions Scenarios) i.e., A1B, B1 and A2, hereafter called climate change scenarios. However, only the climate change scenario A1B was used in the case of the CNCM global climate model. A1B represents a balanced scenario corresponding to atmospheric concentrations of 541 ppm by 2046–2065 and increasing to 674 ppm by 2081–2100. It is the closest to the current Representative Concentration Pathway 6 (RCP 6) (Moss et al., 2010). The climate change scenario B1 is more optimistic and is close to the current RCP 4.5, whereas the climate change scenario A2 is more pessimistic and is close to the current RCP 8.5 (Knutti and Sedlacek, 2013). In our study, changes in the future were analyzed by focusing on 3 climatic periods: 2010–2039, 2040–2069, and 2070–2099, while the historical reference is: 1980–2009.

All our calculations were carried out for two distinct varieties in terms of precocity in order to evaluate the impacts of climate change on short and long-cycle maize varieties: Meribel and dkc5783 (hereafter referred to as early and late varieties respectively, Brisson and Levrault, 2010). From the sowing dates calculated between 1950 and 2100, we computed the calendar dates of the crop phenological cycle for both varieties by using a growing degree day model with a base temperature equal to 6 °C (Bloc and Gouet, 1978; Derieux and Bonhomme, 1990). The sums of degree days characterizing the phenological phases of the two varieties are presented in Table 1.

Daily soil water content (SWC, in g/g) data between 1950 and 2100 for the three climate change scenarios were obtained from the soil

Table 1
Sums in degree days characterizing the phenological phases of both varieties. The corresponding Zadoks scale stages are given in brackets.

Phenological phases	Sum in degree days for Meribel (early variety)	Sum in degree days for dkc 5783 (late variety)
From sowing (Z0) to emergence (Z10)	80	80
From emergence (Z10) to 8-leaves stage (Z30)	240	240
From 8-leaves stage (Z30) to flowering (Z65)	585	805
From flowering Z65) to physiological maturity (Z85)	600	750

water reserve (SWR, in mm) computation at a daily time step by considering soil as a single reservoir. SWR was calculated as follows:

$$SWR_i = \min[SWR_{i-1} + R_i - (ETP_i * Ks_i * Kc_i), SWR_{sat}] \quad (1)$$

where R_i, ETP_i, Ks_i, Kc_i and D_i are respectively rainfall, reference evapotranspiration, crop coefficient, water stress reduction coefficient and drainage on day I, and SWR_{sat} is the soil water reserve at saturation.

Even if maize is usually irrigated in the studied areas, we focused on rain fed production systems, in order to identify the impact of climatic conditions on maize suitability. The ETP, Kc and Ks variables were computed according to the FAO procedure (Allen et al., 1998). The model was initialized at the sowing date by making the assumption that SWR on that day was equal to the useful water reserve. When the soil is saturated ($SWR = SWR_{sat}$), it is assumed that the soil water reserve decreases to the useful water reserve in two days.

In the study, we used one type of soil statistically representative of French soils covered by cereal crops, listed in the French soil database operated by INRA Infosol and used for the CLIMATOR project (Brisson and Levrault, 2010). This soil was leached, 140 cm deep, with a useful water reserve of approximately 226 mm and a soil water content at field capacity equal to 24.14 g/g.

2.2. Overview of the method to evaluate crop-climate suitability and its application to the case of grain maize

The method has three main steps (Fig. 2). First we computed the calendar dates of the crop phenological cycle, from sowing (calculated as described in Section 2.2.2) to physiological maturity. This allows us to characterize the climatic suitability in terms of phenology in a given area for a given variety and sowing date. Physiological maturity needs to be reached before a rational date (December 31st in the case of maize) otherwise we conclude that the climate is unsuitable for this crop variety at this location.

The main meteorological stresses affecting crop suitability in terms of growth cycle, grain quality, and number of days available to carry out cultural practices were then computed. They are used to define ecoclimatic indicators (i.e. agroclimatic indicators calculated over phenological periods) as previously proposed by Caubel et al. (2015) and Holzkämper et al. (2013) and are calculated for each given area, variety and sowing date. Heat stress around flowering is an example of such indicators, as it affects reproductive growth.

Finally, the method normalizes the ecoclimatic indicators through ecophysiological or agronomic response functions in order to compare and prioritize the various stresses. A normalized index equal to 1 means an optimal crop performance regarding the meteorological stress effect, while a value of 0 represents a maximum value of stress.

2.2.1. Ecoclimatic indicators characterizing crop-climate suitability for grain maize

The ecoclimatic indicators used here and their normalization are presented in Table 2 (from Caubel et al., 2015). They have been selected according to scientific literature (Holzkämper et al., 2013; Farré and Faci, 2009; Lorgeou and Souveran, 2003; Bradford, 2002; Crafts-Brandner and Salvucci, 2002; Lang and Müller, 1999; Girardin, 1999; Die Landwirtschaft, 1998; Decker et al., 1986) and expert assessment (Josiane Lorgeou from ARVALIS – Institut du Végétal, French applied agricultural organization dedicated to arable crops). Climatic impacts on maize ecophysiology were analyzed by estimating the effects of water excess, water deficit, cold stress, frost, radiation deficit, heat stress and heavy rain, on vegetative growth, reproductive growth and crop mortality. Indicators have been calculated over specific phenological periods: from sowing (Z0, Zadoks scale, Zadoks et al., 1974) to emergence (Z10), from emergence to 8-leaves stage (Z30), from emergence to meiosis (Z39), from meiosis to flowering (Z65), around meiosis and flowering, and from flowering to physiological maturity (Z85).

The climate suitability for maize regarding days available to carry out cultural practices was evaluated considering:

- an upper threshold of wind speed hampering the application of chemical treatment in sensitive phenological phases (between emergence (Z10) and 8-leaves stages (Z30))
- the effect of water excess in the soil on days available to carry out sowing and harvest operations.

Finally, we assessed the future impacts on grain quality by considering that delayed harvest because of soil water excess increased the risk

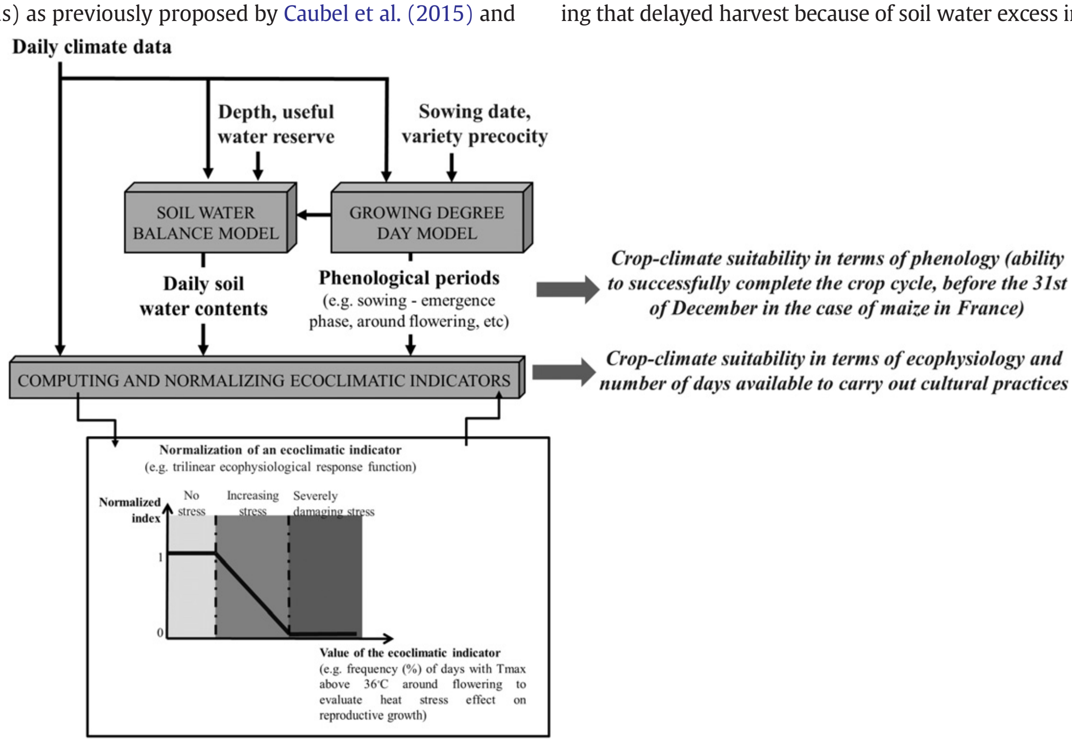

Fig. 2. Method to evaluate crop-climate suitability.

Table 2
Ecoclimatic indicators (and their normalization) calculated to evaluate the climate suitability for grain maize – Z. = Zadoks stage; Quadri. = quadrilinear function; Tri. = trilinear function; Tmin = daily minimal temperature (°C); Tmax = daily maximal temperature (°C); Tmean = daily mean temperature (°C); SWR = soil water reserve (mm); RAW = amount of readily available water for maize (mm) = 0.55 × Useful water reserve; SWC = soil water content (g/g); SWCfc = soil water content at field capacity (g/g).

Crop-climate suitability in terms of	Phenological phase	Ecophysiological process/cultural practices	Meteorological effect	Ecoclimatic indicator (normalization)
Ecophysiology	From sowing to emergence (Z10)	Vegetative growth	Water excess/deficit	Frequency (%) of days with rain ≥5 mm (Quadri. xmin = 20; ×1 = 45; ×2 = 60; xmax = 80; y1 = 0; y2 = 1)
			Cold stress	Number of days with Tmin < −1 °C (Tri. ×1 = 2; ×2 = 9; y1 = 1; y2 = 0)
		Crop mortality	Frost	Number of spells (3 consecutive days) with Tmin < −6 °C (Tri. ×1 = 0; ×2 = 2; y1 = 1; y2 = 0)
			Heavy rain	Number of days with rain >30 mm (Tri. ×1 = 0; ×2 = 3; y1 = 1; y2 = 0)
	From emergence to 8 leaves (Z30)	Vegetative growth	Cold stress	Frequency (%) of days with Tmean <8 °C (Tri. ×1 = 10; ×2 = 100; y1 = 1; y2 = 0)
			Water deficit	Frequency (%) of days with SWR < RAW (Tri. ×1 = 20; ×2 = 60; y1 = 1; y2 = 0)
			Water excess	Frequency (%) of days with SWC > SWCfc (Tri. ×1 = 45; ×2 = 80; y1 = 1; y2 = 0)
		Crop mortality	Frost	Number of spells (3 consecutive days) with Tmin < −6 °C (Tri. ×1 = 0; ×2 = 2; y1 = 1; y2 = 0)
	From emergence (Z10) to Meiosis (Z39)	Vegetative growth (Z10 to Z39)	Water deficit	Frequency (%) of days with SWR < RAW (Tri. ×1 = 20; ×2 = 60; y1 = 1; y2 = 0)
	From meiosis (Z39) to flowering (Z65)	Reproductive growth (Z.39 to Z65)	Water excess	Frequency (%) of days with SWC > SWCfc (Tri. ×1 = 45; ×2 = 80; y1 = 1; y2 = 0)
	Around meiosis (Z39 + 3 days to Z39 + 10 days)	Reproductive growth	Radiation deficit	Average solar radiation (MJ/m^2/days) (Tri. ×1 = 80; ×2 = 160; y1 = 0; y2 = 1)
			Cold stress	Frequency (%) of days with Tmean <4 °C (Tri. ×1 = 10; ×2 = 40; y1 = 1; y2 = 0)
	Around flowering (Z65–5 days to Z65 + 7 days)	Reproductive growth	Heat stress	Frequency (%) of days with Tmax >36 °C (Tri. ×1 = 0; ×2 = 50; y1 = 1; y2 = 0)
			Water deficit	Frequency (%) of days with SWR < RAW (Tri. ×1 = 20; ×2 = 60; y1 = 1; y2 = 0)
	From flowering (Z65) to physiological maturity (Z85)	Reproductive growth	Radiation deficit	Average solar radiation (MJ/m^2/days) (Tri. ×1 = 80; ×2 = 160; y1 = 0; y2 = 1)
			Heat stress	Frequency (%) of days with Tmax >35 °C (Tri. ×1 = 0; ×2 = 50; y1 = 1; y2 = 0)
			Cold stress	Number of days with Tmin < −1 °C) (Tri. ×1 = 2; ×2 = 9; y1 = 1; y2 = 0)
			Water deficit	Frequency (%) of days with SWR < RAW (Tri. ×1 = 20; ×2 = 60; y1 = 1; y2 = 0)
			Frost	Number of spells (3 consecutive days) with Tmin < −6 °C (Tri. ×1 = 0; ×2 = 2; y1 = 1; y2 = 0)
Days available for cultural practices	From emergence (Z10) to 8 leaves stage (Z30)	Pesticide treatments	Wind conditions	Frequency of days with wind speed > = 5 m/s
	Around emergence (Z0–15 days to Z0 + 15 days)	Sowing	Water excess (field workability)	Frequency (%) of days with SWR < RAW (Tri. ×1 = 20; ×2 = 60; y1 = 1; y2 = 0)
Grain quality and days available for cultural practices	After physiological maturity (Z85 to Z85 + 20 days	Harvest	Water excess (field workability)	Frequency (%) of days with SWR < RAW (Tri. ×1 = 20; ×2 = 60; y1 = 1; y2 = 0)

of early grain germination (ARVALIS - Institut du Végétal). We therefore used the same ecoclimatic indicator as for days available to carry out harvest (Table 2).

2.2.2. Algorithm to calculate the sowing date

Sowing dates were computed on an annual basis and for each grid cell of the two areas from 1950 to 2100, using a criterion aimed to mimic a farmer's adaptation strategy with the goal to guarantee field workability and successful germination. The logic is as follows: we consider that sowing can only occur when SWC is below or equal to field capacity, in order to enable field workability. This consideration is combined with minimum air temperature equal to or higher than 4 °C, average temperature equal to or higher than 8 °C, and SWR above the easily available reserve (RAW) in the four days after sowing. These latter considerations are based on the fact that farmers generally also rely on meteorological forecasts to anticipate favorable germination after sowing. Each year, the algorithm was run 15 days before and 15 days after the median of the sowing dates calculated over the previous ten years. An advancement of the sowing date has been observed these last 40 years throughout France (around one month earlier in 2010 compared to 1970, PHETEC database – INRA Agroclim), essentially in response to milder temperatures in spring. Consistently, the sowing date selected each year corresponds to the earliest day among the several days favorable to sowing during the examined period. May 20th was set as the first sowing date in 1950 in order to initialize the calculation, as it corresponds to the average sowing date in France at that time (PHETEC database – INRA Agroclim). Even if the recent climate warming is not the only factor explaining the advancement of maize sowing dates these last past years in France, we compared the calculated sowing dates during the 2005–2015 period with the average sowing date in France over the past few years, which is around the April 10th (PHETEC database – INRA Agroclim). The comparison was satisfactory since the calculated sowing dates actually tend towards this date during the 2005–2015 period (results not shown).

2.3. Method of analysis

After computing future sowing dates, our analysis focused on future climate suitability for maize cropping considering phenology, ecophysiology, and days available for carrying out cultural practices, and grain quality. We mainly concentrated on two different forms of outputs/plots:

(i) the spatial distribution and magnitude of meteorological stresses over the climatic periods, in each grid cell (25,110 and 12,960 grid cells for the Midi-Pyrénées and the Ile-de-France regions respectively), considering the 30-year average;
(ii) the inter-annual distribution of meteorological stresses over the climatic periods, considering their average value over all the grid cells belonging to either Midi-Pyrénées or Ile-de-France. Box and whisker plots are then used to quantify the magnitude of inter-annual variability. The significance of the changes between climatic periods were calculated using Tukey's Honestly Significant Difference tests (Lowry, 2008).

The maize phenology and ecoclimatic indicators were computed concurrently with a fixed sowing date (April 10th) corresponding to the average sowing date in France over the last few years and representing a frame of reference. In this way, some of the main findings regarding changes in the future with computed future sowing dates (presented in Section 3) have been compared with findings for a fixed sowing date (Section 4).

3. Results

In this section we report on our main findings regarding the changes to be expected in the future, in both regions, for both maize varieties with computed sowing dates. We first report on the phenological feasibility of maize cropping (Section 3.1). In grid cells where a crop cannot achieve its full growth cycle prior to the end of the calendar year we do not compute meteorological stress. Whenever crops complete their growth cycle all meteorological stresses listed in Table 2 are calculated and only those that do show non-negligible changes (Sections 3.2 and 3.3) will be discussed below.

3.1. Future impacts on maize phenology

Fig. 3 displays the time evolution of the sowing dates in both regions between 1950 and 2100. In the past and in the future, whatever the scenario, model or location, the sowing date shows a decreasing trend. That means that sowing starts earlier from year to year, albeit with large inter-annual variability (~10–15 days). By the end of the century, the advance of sowing compared to the decades 1980–2009 is as large as 1 month in Midi-Pyrénées, i.e. between late-February (A1B/A2 scenarios × ARPEGE model combinations) and early/mid-March (B1 scenario × ARPEGE model and A1B scenario × CNCM model combinations) compared to mid-April today. This is more than what we find in Ile-de-France, where change amounts to 20 days (compared to the decades 1980–2009), i.e. around mid-April at the end of the century (Fig. 3b, Table 3).

Earlier sowing dates together with rising temperatures lead to earlier phenological stages in both areas (Table 3). Flowering is expected to occur around 3 weeks earlier at the end of the century (compared to the decades 1980–2009), i.e., between mid/end-June for the early variety in Midi-Pyrénées and end-July for the late variety in Ile-de-France. Physiological maturity is expected to occur around 50 days earlier at the end of the century (compared to the decades 1980–2009) for the late variety in Ile-de-France, i.e. around mid/end-September, and 25 days earlier for the early variety in Midi-Pyrénées, i.e. around early-August. In Ile-de-France, the early beginning of grain filling during summer together with the expected rising temperatures lead to a shorter grain filling phase (around 20–30 days less, depending on the climate change scenario × climate model × variety combination).

As a consequence, the early variety of maize that did not complete its phenological cycle in some parts of Ile-de-France over the decades 1980–2009 (Fig. 4-1, A1B scenario × ARPEGE model combination) is expected to grow everywhere starting with the upcoming decades (2010–2039). The late variety however will have to wait until late in the century (i.e. 2070–2099) to be grown safely everywhere in the area (Fig. 4–2, A1B scenario × ARPEGE model combination). Moreover, a spatial heterogeneity of the temperatures linked to urbanization (Paris for the Ile-de-France region) is noticeable, especially for the late variety. In Midi-Pyrénées, areas at altitude (Pyrénées and Massif Central) also benefit from the rising temperatures in the future: crop is expected to complete its crop cycle in virtually the whole area for the 2040–2069 period

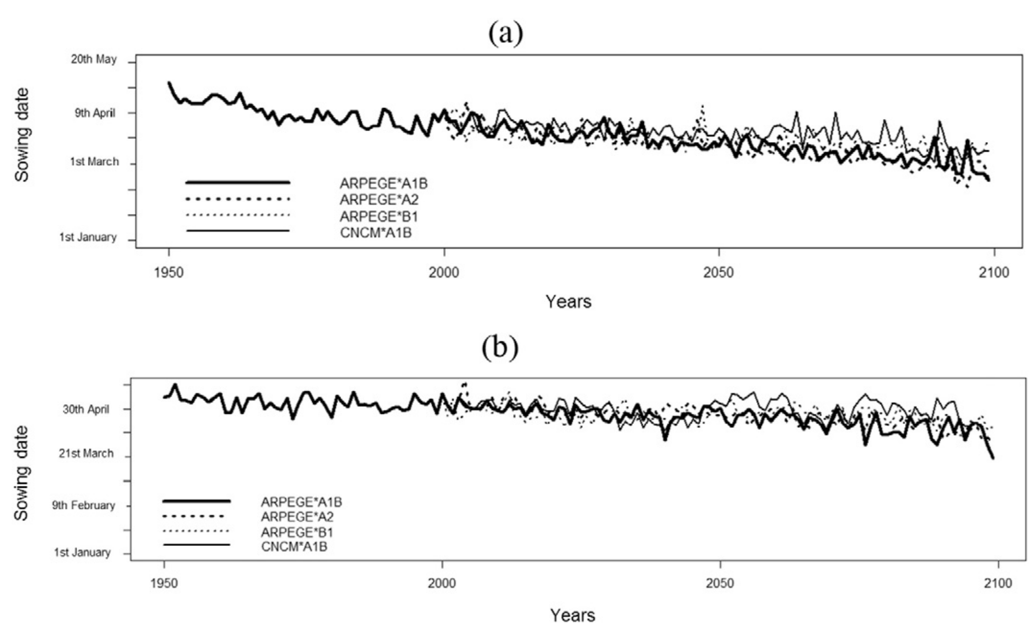

Fig. 3. Calculated sowing dates between 1951 and 2100 for all the climate change scenario × climate model combinations in (a) Midi-Pyrénées and (b) Ile-de-France. Every year, the average of the calculated sowing dates of all the grid cells is calculated.

Table 3
Dates of the main phenological stages of maize (mean and standard deviation) over the 4 climatic periods for the early and late varieties and both areas, for all SRES scenarios and global climate models. Dates are written as day/month, standard deviation is in days.

Phenological stages	Early variety –Midi-Pyrénées region								Late variety –Midi-Pyrénées region							
	1980–2009		2010–2039		2040–2069		2070–2099		1980–2009		2010–2039		2040–2069		2070–2099	
	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*
Sowing (Z0)	12/4	*11.9*	1/4	*15.1*	22-mars	*13.4*	13/3	*13.5*	12/4	*11.9*	1/4	*15.1*	22/3	*13.4*	13/3	*13.5*
Emergence (Z10)	27/4	*11*	18/4	*13.8*	09-avr	*13.9*	30/3	*14.2*	30/4	*8.2*	22/4	*11.2*	10/4	*13.7*	31/3	*14.8*
Flowering (Z65)	14/7	*11.4*	8/7	*11.8*	01-juil	*11.9*	24/6	*12.5*	30/7	*12.5*	25/7	*12.8*	15/7	*12.5*	7/7	*13.1*
Phys. maturity (Z85)	25/8	*15.6*	18/8	*15.3*	09-août	*15*	1/8	*15.5*	24/9	*18.4*	15/9	*18.1*	2/9	*17.6*	21/8	*17.6*

Phenological stages	Early variety –Ile-de-France region								Late variety –Ile-de-France region							
	1980–2009		2010–2039		2040–2069		2070–2099		1980–2009		2010–2039		2040–2069		2070–2099	
	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*
Sowing (Z0)	2/5	*5.9*	26/4	*6*	24/4	*6.2*	16/4	*8.9*	2/5	*5.9*	26/4	*6*	24/4	*6.2*	16/4	*8.9*
Emergence (Z10)	13/5	*5.4*	8/5	*5.6*	5/5	*5.9*	27/4	*8.6*	13/5	*5.4*	8/5	*5.6*	5/5	*5.9*	27/4	*8.5*
Flowering (Z65)	31/7	*6.1*	25/7	*6*	20/7	*6.3*	12/7	*8.2*	17/8	*7.2*	10/8	*6.7*	5/8	*7.1*	27/7	*8.8*
Phys. maturity (Z85)	26/9	*16.8*	13/9	*11.5*	3/9	*10.8*	22/8	*11.7*	11/11	*23.9*	30/10	*24.2*	12/10	*22.8*	21/9	*20.4*

for the early variety and from the 2070–2099 for the late variety (results not shown).

3.2. Meteorological stress effects on maize ecophysiology in the future

3.2.1. Cold stress, risk of frost and water stress at the beginning of crop cycle are expected to increase in Midi-Pyrénées for both varieties, especially for the warmest climate change scenarios

A significant increase in the frequency of days with Tmin < −1 °C between sowing (Z0) and emergence (Z10) is expected in the future for both varieties for the decades 2040–2069 irrespective of the climate change scenario and global climate model considered. This increase in the risk of frost will affect crop emergence (*p*-value of the normalized index <0.05). Changes from 1950 to 2100 of the ecoclimatic indicator and its normalized index are shown in Supplementary material (Fig. S1-1a and S1-1b) for the A2 scenario × ARPEGE model × late variety combination. Moreover, this frost risk is expected to be more and more frequent in the future. Indeed, while no frost risk was observed during the decades 1980–2009, it is expected to occur between 1-in-10 years and 1.6-in-10 years for the decades 2070–2099 (depending on the climate change scenario).

Regarding cold stress affecting maize growth, the frequency of days with Tmean <8 °C between emergence (Z10) and the 8-leaves stage (Z30) seems to increase significantly for both varieties for the decades 2040–2069 in the case of the A1B and A2 scenarios (see Supplementary Material, Fig. S1-3a and S1-3b). This cold stress is also expected to occur more frequently, as 5-in-10 years is expected to be concerned by at least one cold stress day during the 2070–2099 climatic period, compared with 2.5-in-10 years during the 1980–2009 climatic period.

Finally, concerning water stress (here referring to insufficient water) affecting maize emergence, the frequency of days with rain ≥5 mm between sowing and emergence and the normalized index are expected to decrease significantly (*p*-value <0.05) for the decades 2070–2099 for the A2 scenario × ARPEGE model combination (see Supplementary material, Fig. S1-2a and S1-2b).

The increase of these stresses in this area is mainly explained by the advancement of the sowing date during dryer and colder periods. Conversely, these stresses are not expected to increase in Ile-de-France because calculated sowing dates in the future are less anticipated, the course of temperatures rising faster than the anticipation of the sowing dates.

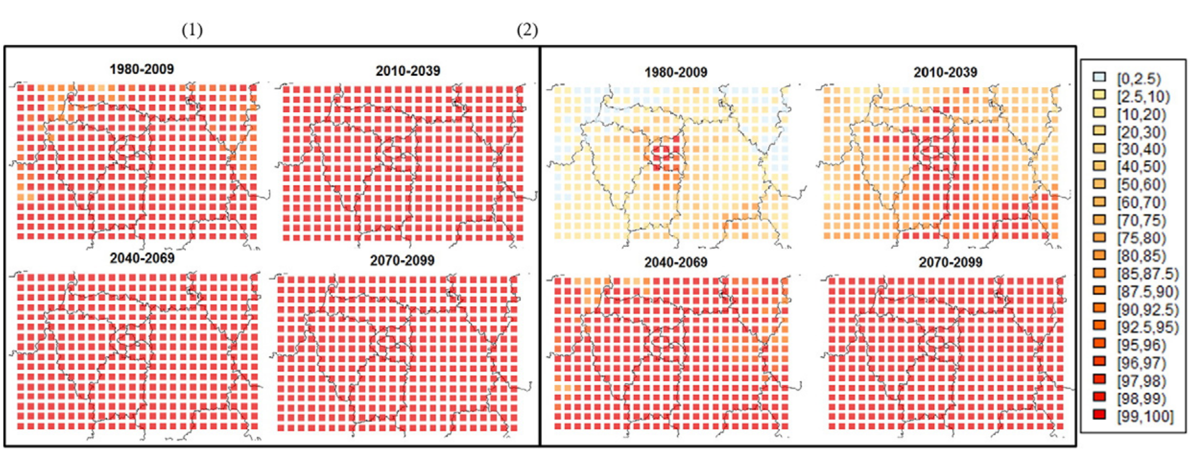

Fig. 4. Percentage of successful crop cycle completion for each grid cell in Ile-de-France region over the 1980–2009, 2010–2039, 2040–2069 and 2070–2099 climatic periods for A1B scenario × ARPEGE model combination in the case of the (1) early variety and (2) late variety.

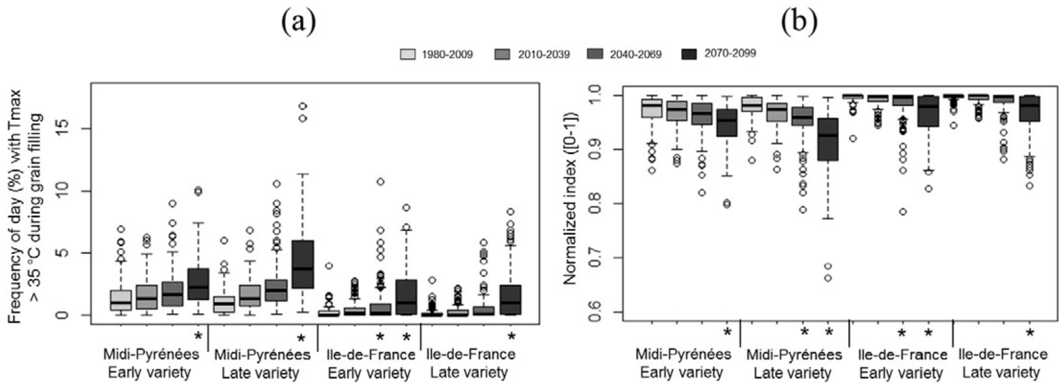

Fig. 5. Box & Whisker Plots showing the interannual distributions over the 1980–2009, 2010–2039, 2040–2069 and 2070–2099 climatic periods for both areas, both varieties as well as all the climate change scenarios and global climate models for (a) the frequency of days with maximal temperature above 35 °C between flowering (Z65) and physiological maturity (Z85) and (b) its normalized index (parameter values of the trilinear function in Table 1) - * indicates significant differences of the climatic period regarding the 1980–2009 period (Tukey HSD test).

3.2.2. Heat stress and water stress are expected to increase between flowering and physiological maturity in both areas and for both varieties

A significant increase in the frequency of days with Tmax > 35 °C and its inter-annual variability between flowering and physiological maturity is expected in the future, irrespective of the climate change scenario × climate model × variety × area combination (Fig. 5a). Such an increase will affect grain filling and therefore yield. This increase seems statistically significant (p-value <0.05) for the entire second half of the 21st century in Ile-de-France for the early variety and only for the decades 2070–2099 in Ile-de-France (for the late variety) and in Midi-Pyrénées, although the number of days exceeding the given threshold of 35 °C does increase consistently with climate warming. Moreover, this risk is expected to be more and more frequent in the future. As an example, for the A2 scenario (warmest scenario), at least one heat stress day during grain filling at the end of the century was assessed 8-in-10 years for the late variety in Midi-Pyrénées and 6-in-10 years for the early variety in Midi-Pyrénées and for both varieties in Ile-de-France (compared to 3.3-in-10 years over the decades 1980–2009 for both areas and varieties). The normalization we proposed (Table 2) considers a severe stress (normalized index equal to 0) only when >50% of the grain filling period was affected by heat stress, i.e. the normalized index decreases linearly from 1 to 0 between 0% and 50% of days with Tmax > 35 °C between flowering and physiological maturity. Concerning changes in the normalized index (Fig. 5b), the lowest normalized values in Midi-Pyrénées may decrease to 0.65 at the end of the century, especially for late varieties, but the median is still expected to be high (0.93). In Ile-de-France, the inter-annual variability of the normalized index is lower than what is expected in Midi-Pyrénées, except over the 2070–2099 decades for which heat stress affecting grain filling is expected to occur more often with lower normalized values reaching 0.85. This represents a shift with respect to current conditions, given that maize growing in Ile-de-France currently does not suffer heat stress.

The frequency of days with a soil water reserve (SWR) below the easily available water reserve (RAW) between flowering and physiological maturity seems to increase significantly for the decades 2010–2039 (Fig. 6a). Such an increase will also affect grain filling and therefore yield. Water stress was already noticeable in the recent past (1980–2009 period) and much higher in Midi-Pyrénées. To normalize, we considered that when >60% of the grain filling period is affected by water stress, the normalized index is equal to zero (severely damaging stress). Normalized results (Fig. 6b) show that the normalized index drops significantly for both areas and varieties, the worst situation occurring for the late variety in Midi-Pyrénées. However, results show a high inter-annual variability of the ecoclimatic indicator, irrespective of the area, variety, and climate change scenario and climate model, making it difficult to assess the future impacts of water stress on grain filling.

3.2.3. Solar radiation conditions between flowering and physiological maturity are expected to increase in Ile-de-France for both varieties

In current conditions, daily solar radiation received by maize crops during grain filling was never limiting in Midi-Pyrénées, whereas it was in Ile-de-France. Our results show that the amount of solar radiation in Ile-de-France will be sufficient in the future, due to the

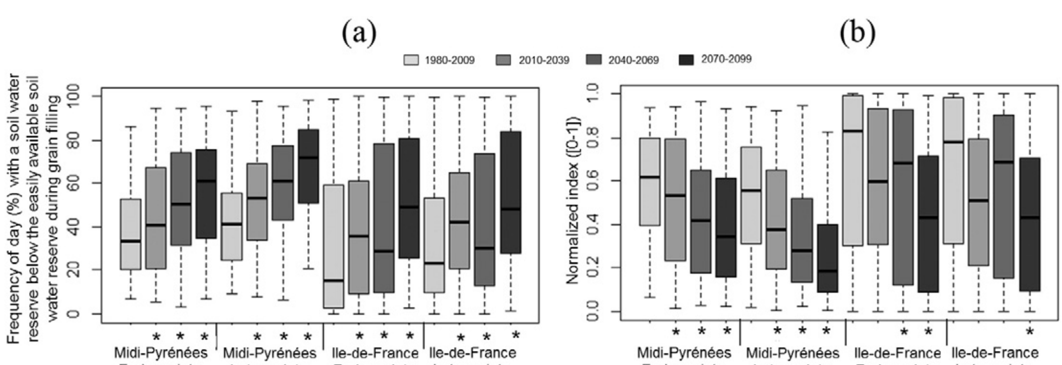

Fig. 6. Box & Whisker Plots showing the interannual distributions over the 1980–2009, 2010–2039, 2040–2069 and 2070–2099 climatic periods for both areas, both varieties as well as all the climate change scenarios and global climate models for (a) the frequency of days with a soil water reserve (SWR) below the easily available soil water reserve (RAW) between flowering (Z65) and physiological maturity (Z85) and (b) its normalized index (parameter values of the trilinear function in Table 1) - * indicates significant differences of the climatic period regarding the 1980–2009 period (Tukey HSD test).

anticipation of the beginning of grain filling during summer. Solar radiation can limit maize growth under 160 W/m^2/day. According to this assumption, daily solar radiation conditions are expected to be no more limiting for grain filling from 2050 for all climate change scenarios × ARPEGE model × variety combinations (see Supplementary material, Fig. S2).

3.3. Meteorological stress effects on grain quality and on days available to perform cultural practices

3.3.1. The days available to carry out sowing are expected to increase in Midi-Pyrénées for the warmest scenarios

In Midi-Pyrénées, the frequency of days with SWC above field capacity around the sowing date is expected to decrease in the future for the warmest scenarios (Table 4). This decrease seems significant (p-value <0.05) for the decades 2070–2099 for the A1B scenario × ARPEGE model combination and for the decades 2040–2069 for the A2 scenario × ARPEGE model combination. We could then expect an increase of the days available to carry out sowing according to field workability. Conversely, no significant trend is expected for the B1 scenario × ARPEGE model and A1B scenario × CNCM model combinations in this area, and not in Ile-de-France either (Table 4b). This can be explained by greater anticipation of calculated sowing dates in the future for the warmest scenarios in Midi-Pyrénées, which leads to sowing periods occurring before the occurrence of precipitation in spring.

3.3.2. The number of days available for pesticide spraying is expected to decrease in Midi-Pyrénées for both varieties

The frequency of days (%) with wind speed above 5 m/s between emergence (Z10) and 8-leaves stage (Z30) clearly increases in Midi-Pyrénées for both varieties regardless of the climate change scenario and the global climate model. Such an increase will affect the number of days available for pesticide spraying. Nevertheless, this increase is strongly localized and assigned to the Mediterranean area for the A1B scenario × ARPEGE model × late variety combination (see Supplementary material, Fig. S3). At the same time, we do not observe any change of wind conditions in Ile-de-France (results not shown).

3.3.3. The number of days available for harvest is expected to increase in both areas and for both varieties, together with the grain quality

The frequency of days with SWC above SWC at field capacity during the twenty days following the predicted physiological maturity is expected to significantly decrease for both areas and varieties regardless of the climate change scenario and global climate model. This can be explained by the advancement of the crop cycle which enables autumn rain events to be avoided. In Midi-Pyrénées, the risk was already very low in the recent past (1980–2009). However, the decrease is greater in Ile-de-France: this expected improvement of harvesting conditions, and therefore of grain quality is noticeable from 2010 for the early variety and from 2050 for the late variety, as shown in Fig. 7 in the case of A1B scenario × ARPEGE model combination.

4. Discussion

4.1. Analysis of the results

Sowing dates calculated by our method are expected to advance in the future, especially in Midi-Pyrénées. This result is consistent with observations over the last 40 years in France (around one month earlier from 1970, PHETEC database – INRA Agroclim). The results we obtained in Ile-de-France for the near future are consistent with Olesen et al. (2012) who predicted an earlier sowing date of spring cereals in Europe of 1–3 weeks by 2040, depending on the climate model and region within Europe. Our study also considers southern Europe areas and changes in the distant future, whereas Olesen et al. (2012) focused on Northern and Central Europe by 2040. Furthermore, Trnka et al. (2011) showed that the number of suitable days for sowing crops will increase in the future except in southern areas of the Mediterranean basin. Our approach did not consider suitable sowing days but rather sowing dates derived from farmers' adaptation to future climatic conditions. Our results can thus integrate previous findings to define new adaptation strategies to better choose the maize sowing time.

Concerning crop-climate suitability in terms of phenology, our study shows that rising temperatures in the future will be favorable for late varieties in the cooler areas (North of France and areas at altitude), because of an anticipation of flowering and physiological maturity when solar radiation is optimal for maize grain filling. Caubel et al. (2015) showed that the increase of surface area covered by maize in a north-eastern region of France over past years may be attributed to the same factors. This was consistent with and independent of the sowing date. Indeed, future changes regarding successful crop cycle completion of the late variety in the Ile-de-France by using a fixed date (April 10th) are the same as those obtained with sowing dates calculated by our method (results not shown). The gap between Ile-de-France and

Table 4
Frequency of days with SWC above field capacity (mean and standard deviation) around the sowing date (from 15 days before to 15 days after the calculated sowing date) in Midi-Pyrénées over the 4 climatic periods for the different SRES scenario x climate model combinations.

Scenario × climate model combination	1980–2009		2010 –2039		2040 –2069		2070–2099	
	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*	Mean	*sd.*
A2 scenario × ARPEGE climate model	32.82	*20.25*	35.58	*20.35*	26.22	*15.01*	15.91	*13.37*
A1B scenario × ARPEGE climate model	33.68	*19.66*	35.91	*16.83*	26.40	*21.62*	20.51	*14.72*
B1 scenario × ARPEGE climate model	32.31	*21.54*	28.76	*18.62*	26.70	*18.51*	28.77	*16.44*
A1B scenario × CNCM climate model	34.66	*20.21*	33.42	*19.90*	26.16	*13.57*	32.54	*18.05*

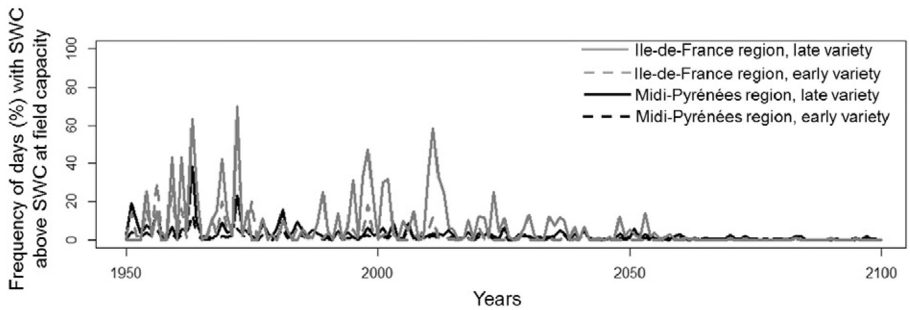

Fig. 7. Frequency of days with soil water content (SWC) above the SWC at field capacity during the twenty days following the predicted physiological maturity for each area (average value of all the grid cells and each variety between 1950 and 2100 for the A1B scenario × ARPEGE model combination.

Midi-Pyrénées in terms of climate suitability regarding maize phenology will decrease in the future (Fig. 4). Consequently, even farmers in Ile-de-France will be able to grow varieties with a wide range of crop cycle length. In this study, we used a thermal time approach which assumes a linear relationship between temperature and development (Bloc and Gouet, 1978; Derieux and Bonhomme, 1982). This approach is prevalent in scientific literature, even if it is known that limiting water conditions and high temperatures can slow the rate of crop development (Ceglar et al., 2011). These effects would be most interesting to consider in the context of climate change but are still not well characterized. Moreover, for grapevine development and in a context of warmer conditions in France, Cuccia et al. (2014) showed little difference in predictions between a non-linear model of temperature and a simple linear temperature summation model. According to these results we hypothesized that the use of a conventional linear model would not significantly impact final results.

Concerning crop-climate suitability in terms of ecophysiology, we showed that both Midi-Pyrénées and Ile-de-France are expected to be more affected by heat and water stress during the grain filling, particularly in Midi-Pyrénées. As for phenological changes, changes of climate suitability in terms of ecophysiology have also been analyzed with a fixed sowing date (data not shown): no significant differences appear between the two strategies, revealing that earlier sowing dates do not help to avoid the dry and hot season's stresses as much as we may have expected. Water stress in Midi-Pyrénées and for the late variety will particularly increase in the future, because of an expected decrease in the total amount of rainfall. Caubel et al. (2015) showed that maize irrigation was able to maintain an optimal climate suitability over recent years in a southern French location (Toulouse). Nevertheless, it is questionable whether it will be the same in the future (constrained rules for limiting irrigation, rising costs of water and rising water stress). In this sense, the use of earlier varieties with higher water use efficiency represents an effective strategy in these areas to limit the impact of the water deficit on maize production and quality. Moreover, it should also be noted that the study was performed for only one type of soil statistically representative of French soils covered by cereal crops. Ruane et al. (2013) who investigated the effect of season length, planting date, fallow period, soil type, cultivar choice and fertilizer use on maize growth in Panama found that soil type is an important driver of maize yield. The consideration of a set of soils in terms of depth and useful water reserve would therefore enable a more robust outlook of future trends and adaptations specific to different soil typologies.

Still regarding crop-climate suitability in terms of ecophysiology, the excessively early sowing dates calculated by our method in Midi-Pyrénées will bring out cold and frost stresses at the beginning of the crop cycle. In this context, the positive effect of sowing date anticipation (Tsimba et al., 2013) may be counteracted by the occurrence of new types of stress. This impact has been studied for winter crops (i.e. Barlow et al., 2015) or perennial crops (i.e. Fraga et al., 2016), but to our knowledge not for maize.

Finally, concerning crop-climate suitability in terms of days available to perform cultural practices, our results show more available days to harvest in both areas because of lower rainfall after physiological maturity, independently of the varieties and scenarios tested. This information is important in order to define priorities when developing adaptation strategies. Despite the increase in heat and water stresses during the maturity period, better grain quality is expected in the future. However, we only considered the effect of excess water after physiological maturity which involves early grain germination. Grain quality (organoleptic and nutritional quality) is an important topic that should be studied in more depth in the future in the context of food security policies (Gustafson et al., 2016). Finally, we have observed an important increase in windy days in Midi-Pyrénées, probably due to the advance of the whole crop cycle. This change could probably alter farmers' capacities to apply different treatment in the field (pesticides, fertilization, etc.). This result should also be regarded in a context of political efforts in the European Union to reduce pesticide use even if this goal is challenging due to several species of pests causing increasing problems (Meissle et al., 2010). However, there is considerable uncertainty around future climate forecasts regarding wind. Current research is scarce (Carvalho et al., 2017; McVicar et al., 2012) and needs to be more in depth in order to confirm (or refute) the result we obtained.

4.2. Advantages and limitations of the method

The strength of our methodology is the computation of agroclimatic indicators during different phenological periods, in order to provide information on the effects of meteorological stresses on plant processes occurring in specific development phases that are subject to shift according to temperature conditions during the year. Agroclimatic indicators have been widely used in scientific literature to evaluate the effects of climate in a given area on crop productivity, crop management or environment (Holzkämper et al., 2013; Holzkämper et al., 2015; Trnka et al., 2014; Rötter et al., 2013; Trnka et al., 2011; Confalonieri et al., 2010; Mkhabela et al., 2010; Dubrovsky et al., 2009; Matthews et al., 2008), but few of them consider the crop phenological cycle. Moreover, we have only presented results related to individual meteorological stresses in this study. But, the methodology also helps combine the normalized indices into a global index of climate suitability providing overall and synthetic information. Rules of aggregation are presented and illustrated in Caubel et al. (2015).

In addition, the method is generic and flexible enough to perform a general assessment of future meteorological stresses impacts on phenology, growth cycle, grain quality and performance of cultural practices. The method requires relatively few inputs, which made it possible to perform the study for a set of climate scenarios × climate models × varieties (distinct in terms of precocity) combinations in order to take into account the main sources of uncertainty in climate change studies.

As described by Holzkämper et al. (2015) the evaluation of climatic effects on crops is based on temporally aggregated explanatory variables and not on occasional (e.g. extreme) events. For this reason, even if ecoclimatic indicators easily identify local hotspots or specific climatic risks, various modelling approaches (Holzkämper et al., 2015) need to be combined in order to identify all the threats and opportunities.

The methodology does not take into account the impacts of future CO_2 levels on maize ecophysiology. Many experimental studies have shown that a higher CO_2 level increases plant biomass production and yield through an increase of photosynthesis and water use efficiency (Drake et al., 1997; Garcia et al., 1998; Tubiello et al., 2007; Hasegawa et al., 2013). However, the methodology applied in this study aims to assess the periods and the type of meteorological stresses that will affect maize in the future, and not to quantify the biomass (yield) increase, which in some cases is due to a higher CO_2 level. One way to take these benefits into account is to decrease the negative effect of water stress on crop suitability (considering an increase of the water use efficiency). Nevertheless, the scientific literature is not comprehensive enough to define a threshold from which the negative effect of lower rainfall is counter-balanced by the positive effect of an increase in CO_2 concentration. At this point, it may then only be assumed that the strong increase of water stress conditions, which is highlighted in this study (e.g. in Fig. 7), will be partly tempered by the positive impact of a higher CO_2 level and by varietal selection. These results can also be compared with those obtained using crop models (Bassu et, 2014) which take into account this effect, in order to complete both analyses.

The method developed to calculate potential sowing dates provides very interesting results and opens new perspectives to evaluate strategies to adapt cropping systems to climate change. Even if it does not take cyclical decisions into account, the method does consider farmer adaptation to a degree. Nevertheless, the advancement predicted by our method in sowing time does not necessarily result in an increase of climate suitability in terms of ecophysiology, as shown for Midi-Pyrénées. This is mainly due to the fact that we have calculated sowing dates independently of meteorological stresses occurring after germination and without introducing a criterion to reduce some of them (e.g. precipitation for emergence, cold and frost risks at the beginning of the crop cycle, and heat stress during grain filling).

This study demonstrates that many changes will occur at the same time affecting different ecophysiological processes and technical practices. In this context, several strategies will have to be used at plot level (such as the combination of different sowing dates and different varieties with various levels of precocity) and at territory level (restructuring of production areas according to crop-climate suitability) in order to find the best strategy of adaptation to future climatic conditions. Furthermore, the results emphasize the impossibility to identify one single and simple farmer action everywhere, but rather local and adapted solutions in each production area.

5. Conclusion

This study uses a method that allows to assess when and what meteorological stresses will affect grain maize crop in the future in two main production regions in France. This methodology analyzes all the cropping system processes: crop phenology and growth cycle, grain quality and number of days available to carry out the main cultural practices. Similarly, a dynamic method has been developed in order to calculate sowing dates in a way to mimic an adaptation of farmers' behavior to climate change.

Important changes are expected in those regions under future climatic conditions. The sowing date algorithm showed an advance in the potential date in both regions while earlier in Midi-Pyrénées, notably because of the dry conditions. Thus, in Ile-de-France it will be possible to complete the phenological cycle independently of the precocity of the varieties several decades before the end of the 21st century. An increase in heat and water stress is expected in both regions, while higher in Midi-Pyrénées. Frost risk cannot be completely excluded, particularly in Midi-Pyrénées where very early sowing dates can be used in order to try and escape dry and warm conditions at the end of the cycle.

All these results indicate that there is considerable complexity of interactions between risk and phenological periods which complicates the development of adaptation strategies. In some cases, such as in Ile-de-France, the best strategy can be sought from within a wide range of combinations (early – late variety × sites × sowing date × risk assessment). On the other hand, in Midi-Pyrénées, these combinations will be more limited in order to maintain crop suitability and production.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2017.02.010.

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